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THE ATTENUATION CHARACTERISTICS OF FOUR SPECIALLY DESIGNED MUFFLERS TESTED ON A PRACTICAL ENGINE SETUP

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THE ATTENUATION CHARACTERISTICS OF FOUR SPECIALLY DESIGNED MUFFLERS TESTED ON A PRACTICAL ENGINE SETUP

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SUMMARY

This paper presents the results of muffler tests made to evaluate the theoretical resonator-muffler attenuation expression as applied to practical installations. A specific design procedure for the mufflers tested is also included.

Four resonator-type mufflers of different attenuation capabilities were designed and tested on a laboratory cold-test setup and a helicopter field-test setup. Good agreement was found between the laboratory experimental data and theory. The field-test results, however, showed that the mufflers attached to the helicopter did not lower the field noise to the extent predicted by theory or the amount measured in the laboratory test. This attenuation reduction is believed to be due in part to the nonfulfillment of the basic theoretical assumptions of low sound pressures and zero flow velocities and in part to the extraneous noise level.

Although the theoretically predicted attenuation may not be obtained in practical installations, the results show that the resonator equation can be very useful in the design and development of mufflers.

INTRODUCTION

With the power-increase developments made by the light or private-aircraft industry in the past few years and with the rapid expansion of the suburban-home areas, there has been an increasing aircraft-noise disturbance problem in and around airports close to congested areas. This noise problem was brought to the attention of the National Advisory Committee for Aeronautics for special consideration. As a result, a theoretical and experimental muffler investigation at the Langley full-scale tunnel was undertaken, as well as propeller-noise investigations by other NACA research facilities.

Certain phases of the investigation covering dynamometer-stand muffler tests and propeller quieting have been completed and the results are published in references 1 to 3. The theoretical work of reference 4 presents design curves and an equation for predicting the attenuation characteristics of several types of mufflers. One of the muffler types considered in the investigation of reference 4 embodies the principle of chamber resonance. This resonant-chamber muffler appeared to be worthy of additional study because of its large attenuation for a given size and for its low-back-pressure possibilities.

The laboratory tests of reference 4 indicated that resonator-attenuation characteristics can be predicted by theory. These tests, however, were for mufflers having tail pipes terminated in their characteristic impedance, a condition different from that found in practice.

The theoretical developments in reference 4 also provided an equation for calculating the attenuation characteristics of mufflers having finite-length tail pipes. There were no experimental data, however, to show the accuracy of this expression and, in addition, the material in reference 4 indicated that the theoretical assumptions of small sound pressures and zero flow velocity would not be satisfied for mufflers operating under engine-exhaust conditions. For these reasons, a need for both laboratory tests and engine tests was recognized.

The present investigation was therefore undertaken to determine the collective influences, if any, that such factors as (1) tail pipe, (2) large sound pressures, and (3) exhaust flow velocities had on the attenuation characteristics of resonator-type mufflers. In addition, consideration was also given to the design of practical aircraft mufflers.

For an investigation of this nature, it is desirable to have an engine dynamometer stand; however, in this case, a helicopter was used for executing the muffler field test because of its availability. Such an arrangement was expected to be permissible for these tests because of the low extraneous noises generated by the test helicopter rotor.

SYMBOLS

c_o conductivity, ft

f frequency, cps

f_r resonant frequency, cps

l_t length of tail pipe, ft

c speed of sound, fps

V volume of muffler chamber, cu ft

S cross-sectional area of internal tubing in muffler, sq ft

p pressure, psi

$\frac{p_1}{p_3}$ ratio of muffler inlet sound pressure to exit sound pressure

a radius of conductivity opening, ft

l length of conductivity opening, ft

n number of conductivity holes

$k_r = \frac{2\pi f_r}{c}$

f_c cut-off frequency, cps

λ wave length, ft

PRETEST DATA

Before a test such as the one to be discussed in this paper can be effectively undertaken, certain information concerning the operating characteristics of the test equipment must be known: (1) the engine-exhaust noise spectrum must be available so that proper muffler designs can be made, (2) the exhaust-gas temperatures must be known in order that wave lengths may be computed, and (3) the level of the extraneous noise is needed to determine the maximum quieting which can be realized. Because none of this information could be obtained from published material, an initial field test was made to provide this information. Measurements obtained provided a satisfactory exhaust-noise analysis and a useful temperature record. Figure 1 shows the exhaust-noise frequency analysis. Temperature measurements showed the speed of sound in the exhaust pipe to be approximately 2000 feet per second.

The extraneous-noise level, which is herein defined as noise from sources other than the engine exhaust, could not be accurately determined from the pretest data.

MUFFLERS AND DESIGN

In order to insure that an adequate test range would be covered in the investigation, four resonator-type mufflers were designed and constructed. Three of the mufflers had single resonant chambers, whereas the fourth had two resonant chambers. The double-chamber muffler was designed with the intent to provide enough exhaust-noise attenuation so that the extraneous noise level could be measured. Figure 2 shows schematic drawings of these mufflers.

The mufflers were designed to give successive increases in attenuation and to have the acoustical properties shown in the following table:

Muffler	Chamber resonant frequency, cps	Tail-pipe resonant frequency, cps	Attenuation parameter, $\frac{\sqrt{c_oV}}{2S}$
1	280	398	4.33
2	280	580	6.03
3	280	580	12.00
4	140, large chamber 400, small chamber	Undetermined	9.5, large chamber 16.15, small chamber

Mufflers 1, 2, 3, and 4 were made from 1/16-inch mild steel and weighed 12, 17, 21, and 32 pounds, respectively. Figure 3 shows the mufflers installed on the test helicopter.

It may be of interest at this point to indicate the method used in the design of these mufflers with a specific example included for muffler 2. The fact that the test helicopter had two exhaust systems, one exhausting three cylinders and the other exhausting four cylinders, did not require the design of different mufflers for the two exhaust pipes. Although the exhaust-pressure pulse from each cylinder contains components at the individual cylinder firing frequency and at harmonics of this frequency, the phase relationships are such that, when the pressure pulses of all seven cylinders are combined in the atmosphere, the components at the cylinder firing frequency and at many of the harmonics are partially canceled. The mufflers must attenuate those frequency components in both exhaust pipes which combine to cause undesirably high noise levels in the atmosphere. Consequently, the mufflers are designed on the basis of the noise in the atmosphere, rather than that inside the individual exhaust pipes, and, as a result, the two mufflers are identical. The seventh harmonic of the cylinder firing frequency is referred

to as the engine fundamental frequency. The prominence of this harmonic in the unmuffled engine noise (see fig. 1) is due to the fact that this frequency is the lowest at which the components of all seven cylinders are nearly together in phase.

(1) The exhaust-noise spectrum (fig. 1) obtained from the pretest showed that most of the disturbing noise fell in the frequency range from 70 to 350 cycles per second and that 10 decibels of over-all attenuation would reduce the noise to a desired level. The muffler must be made to resonate within this frequency band in order to obtain maximum quieting; thus, 280 cycles per second was chosen for the muffler resonant frequency. In order to provide a 10-decibel reduction from 70 to 350 cycles per second, a muffler having a design parameter $\frac{\sqrt{c_o V}}{2S}$ value of approximately 6.0 was selected from design curves on the basis of the procedure described in reference 4.

(2) A tube for conducting the exhaust gases through the muffler for filtering must be chosen. The engine-exhaust back pressures should be kept small; consequently, a tube used for this purpose must be large enough to keep the back pressure within acceptable limits. The tubing selected for muffler 2 was $2\frac{1}{4}$ inches, the same size as the existing exhaust ducting on the test helicopter. It should be noted that the attenuation parameter $\frac{\sqrt{c_o V}}{2S}$ shows that the internal-tube area governs the muffler size for a given attenuation; for this reason, the tube should be selected as small as practicable.

(3) In order to obtain the length for this central tube, a desired tail-pipe length is computed and added to the length necessary to conduct the exhaust gases to the conductivity holes. The conductivity holes mark the origin of the tail pipe for single-chamber mufflers. Before the tail-pipe length can be computed, however, some specific frequency for tail-pipe resonance must be selected. This frequency must fall within a range in which little or no attenuation is needed because, as the tail-pipe resonant frequency is neared, the muffler attenuation drops to a negative value over a narrow band. The tail-pipe resonant frequency selected for muffler 2 was 580 cycles per second. The tail-pipe length is computed as follows:

$$l_t = \frac{\lambda}{2} = \frac{c}{2f} = \frac{2000 \times 12}{2 \times 580} = 20.68 \text{ inches}$$

By applying an end correction of $\Delta l_t = 0.61R$ (ref. 4) where R is the tail-pipe inside radius, the resulting corrected tail-pipe length is

$$l_t = 20.68 - 0.61(1.125 - 0.063) = 20.03 \text{ inches}$$

Inasmuch as the theory of reference 4 shows that the tail-pipe length also affects the low-frequency cut-off of the muffler, a check is required to see whether this cut-off falls within the desired attenuation band. The cut-off frequency is determined from equation (C12) of reference 4.

$$f_c = \frac{f_r}{\sqrt{1 + \frac{\sqrt{c_o V}}{2S} k_r l_t}} = \frac{280}{\sqrt{1 + 6 \frac{2\pi \ 280}{2000} \frac{20.68}{12}}} = 88 \text{ cps}$$

Since the cut-off frequency is within the frequency band in which muffling was desired, a decision must be made as to whether it is beneficial to increase the tail-pipe length and thereby lower the high frequency cut-off or to increase the chamber size in order to obtain a small attenuation gain in the low-frequency range.

(4) The conductivity factor c_o determines the muffler resonant frequency for a given volume. The equation

$$f_r = \frac{c}{2\pi}\sqrt{\frac{c_o}{V}}$$

shows the relationship that exists among the conductivity, volume, and resonant frequency. With the use of this expression and for the values of the parameters chosen, the volume and conductivity for muffler 2 can be determined as follows:

$$f_r = \frac{c}{2\pi}\sqrt{\frac{c_o}{V}} = 280 \text{ cps}$$

Solving for $\sqrt{\frac{c_o}{V}}$ yields

$$\sqrt{\frac{c_o}{V}} = \frac{280 \times 2\pi}{2000} = 0.880$$

$$\frac{\sqrt{c_oV}}{2S} = 6$$

and solving for $\sqrt{c_oV}$ gives

$$\sqrt{c_oV} = 6 \times 2 \times \frac{\pi}{4} \frac{(2.25 - 0.125)^2}{144} = 0.295$$

$$c_o = \sqrt{\frac{c_o}{V}} \sqrt{c_oV} = 0.880 \times 0.295 = 0.260 \text{ ft}$$

By substitution

$$V = \frac{0.260}{0.880^2} = 0.336 \text{ cu ft}$$

This volume and a chosen muffler length of 2 feet were used to calculate the muffler diameter, 5.9 inches. For the sake of construction simplicity, the diameter was chosen to be 6.0 inches. This diameter change required small adjustments to be made in the values of volume and conductivity; the new values calculated were 0.338 cubic foot and 0.261 foot for volume and conductivity, respectively.

(5) In order to obtain the required muffler conductivity, an expression found in reference 5 may be used. This expression

$$c_o = \frac{\pi a^2}{l + \frac{\pi}{2} a}$$

gives the approximate conductivity of a circular opening having radius a and length l. The number of 1/2-inch holes required for muffler 2

may be computed by using the preceding equation in the following expression

$$n = \frac{c_o \text{ of muffler 2}}{c_o \text{ per 1/2-inch hole}}$$

$$= \frac{0.261}{\dfrac{\pi\left(\frac{1}{4}\,\frac{1}{12}\right)^2}{\frac{1}{16}\,\frac{1}{12} + \frac{\pi}{2}\,\frac{1}{4}\,\frac{1}{12}}} = 7.27 \text{ or } 7 \text{ holes.}$$

Experience has shown that there are some effects on the conductivity caused by the close spacing of holes which often require the number of holes to be changed in order to obtain the desired conductivity c_o, or resonant frequency. The actual conductivity c_o can be determined by experimental tests.

(6) After all dimensions for the muffler have been determined, the theoretical attenuation characteristics of the resonator should be computed and analyzed with the use of equation (C10) of reference 4. This expression may be given in decibels in the following form:

$$\text{Attenuation} = 10 \log_{10}\left(\frac{p_1}{p_3}\right)^2$$

$$= 10 \log_{10}\left[1 + \left(\frac{c}{S}\right)^2 \left(\frac{1}{\frac{2\pi f}{c_o} - \frac{c^2}{2\pi f V}}\right)^2 \sin^2\left(\frac{2\pi f}{c}\right) l_t + \frac{c}{S}\,\frac{1}{\frac{2\pi f}{c_o} - \frac{c^2}{2\pi f V}} \sin\left(\frac{4\pi f}{c}\right) l_t\right]$$

If the predicted attenuation does not conform to the desired conditions, small changes in the originally selected design values may be made to achieve the desired results.

APPARATUS

The test helicopter (fig. 4) was used as the muffler test bed in this investigation. The tail rotor was removed for the tests to prevent its noise from interfering with the sound measurements. The noise emanating at the main rotor fundamental frequency (13 cycles per second) was known to be of little significance in these tests. However, a possibility that the higher harmonics of the rotor might interfere with the exhaust noise measurements was recognized.

The helicopter was powered by a R-550-1, 180-horsepower, 7-cylinder engine having twin exhaust stacks. One stack exhausted three cylinders and the other, four. Figure 5 shows a diagrammatic sketch of the field-test setup and surrounding terrain.

Laboratory cold tests were also conducted in this investigation. These cold tests required the building of a test setup similar to the one shown by the schematic drawing in figure 6. The specific electronic equipment incorporated in this setup was as follows: (1) an audio oscillator; (2) a power amplifier and speaker; and (3) a sound-level meter.

The sound measuring equipment used in the field tests consisted of a General Radio Company type 759-B sound-level meter, a General Radio Company type 760-A sound analyzer, and a Western Electric type 700-A sound-level meter and filter set. Both the frequency analysis and the over-all sound-pressure level were recorded on a twin recorder. This equipment gave an over-all measuring accuracy of about 2 decibels when operating under field conditions. The response of the audio amplifiers and microphones was found to drop rapidly for frequencies below 40 cycles per second. A water-cooled crystal pressure pickup was utilized to obtain a time history of the pressure variation inside the exhaust pipe ahead of the muffler. Indications of the exhaust-gas temperatures were obtained through use of chromel-alumel thermocouples and a Lewis potentiometer.

TESTS

The laboratory cold tests were conducted in the open area behind the Langley full-scale tunnel. The cold-test data were obtained by sending single-frequency sounds into the mufflers and observing the noise reduction produced by the silencer. In order to insure that the mufflers were tested for the same wave lengths in the cold test as in the hot or field test, the cold-test frequencies were adjusted to produce the wave lengths for which the mufflers were designed. In the

presentation of the cold-test results, the experimental frequencies are multiplied by the ratio of the sonic velocity in the actual exhaust gas to the sonic velocity in the cold test in order to correct for the temperature difference between the two conditions. For the cold test, the frequency range was from 30 cycles per second to 400 cycles per second; for the hot test, the frequency range having equal wave lengths is 52 to 700 cycles per second. The ambient noise level for the laboratory tests was about 60 decibels.

The field tests were conducted before sunrise on the Langley landing field. The ambient field noise level was approximately 62 decibels at the start of the field tests. Changes that may have occurred in the ambient field noise after the helicopter engine was started could not be determined. The muffler field tests included the investigation of the four mufflers of different size on the modified helicopter to determine the attenuation characteristics of the mufflers at an engine speed of approximately 2200 revolutions per minute. In order to determine more fully the conditions under which the mufflers were operating, internal exhaust-gas sound pressures and temperatures were measured during one of the test runs.

As a further check on the practicality of the muffler design, the helicopter was flown with the first three mufflers attached. The pilot, who had considerable flying experience with the test helicopter, reported no noticeable change in performance.

RESULTS AND DISCUSSION

The results of these muffler tests, which are discussed in the following sections, show the effectiveness of the muffler in reducing the exhaust noises along with the merits and shortcomings of the theoretical equation under investigation (eq. (C10), ref. 4). The results of these muffler tests are separated and discussed in two different sections entitled "Cold Tests" and "Muffler Field Tests." The muffler experimental results are presented in the forms of tables and curves.

Cold Tests

The experimental results obtained from the muffler cold tests are shown by the small circles in figure 7. The solid lines in this figure show the theoretical attenuation predicted for each muffler. The theoretical data which were computed from the resonator equation showed mufflers 1, 2, and 3 were designed to have chamber resonances (points of maximum attenuation) at approximately 280 cycles per second and tailpipe resonances at about 385, 580, and 580 cycles per second, respectively.

A comparison of the experimental and theoretical data indicated good agreement for all mufflers tested. For example, the higher frequency cut-off points, characterized by tail-pipe length, are seen to fall very close to predicted frequencies, and the measured attenuation throughout the frequency range fell very near that computed theoretically. It may therefore be concluded that the theoretical expression of reference 4 is valid for predicting the attenuation characteristics for muffler-tail-pipe combinations under the cold-test conditions.

Since the mufflers used in this investigation were designed specifically for the engine on which they were to be tested, these cold-test experiments also served to show whether the expected design conditions were met. The double-chamber resonator curve computed for muffler 4 shows two chamber resonance frequencies and no high-frequency tail-pipe pass bands. The difference between curve shapes for the single- and double-chamber mufflers is, of course, due to the changes in the acoustical circuit. The mufflers were not expected to provide the infinite attenuation calculated at the chamber resonant frequencies; the calculated infinite values occurred only because the viscous forces were neglected in order to simplify the calculations.

For the cold tests, the two largest mufflers (mufflers 3 and 4) were wrapped with several layers of felt. In the absence of the felt wrappings, the maximum attenuation was limited to about 25 to 30 decibels by the radiation from the 1/16-inch-thick outer walls. Reduction of this radiation would be an important factor in the design of a muffler from which a higher attenuation is desired.

Muffler Field Tests

The muffler field-test results are shown in figure 8 and table I. These data describe the manner in which the amplitude of the exhaust noise varies with frequency. Figure 8(a) shows the unmuffled-exhaust noise spectrum in addition to the noise spectrums for both mufflers 1 and 2. Similarly, the spectrums for mufflers 3 and 4 are shown in figure 8(b).

Frequency analysis.- The curve describing the envelope for the unmuffled exhaust-noise frequencies shows that the fundamental firing frequency (noted by the dashed line) is by far the largest noise-producing harmonic and thus the frequency which should be given the greatest attenuation. The peaks occurring at 75 and 205 cycles per second are the next largest sound-producing frequencies of the engine noise. These two peaks, along with the fundamental peak mentioned previously, define the frequency band where most of the annoying noise is found to exist and, consequently, the range which should be given the greatest attention. When the noise spectrum from each of the four mufflers is

compared to that of the unmuffled engine, it becomes obvious that considerable muffling was obtained in the 75 to 205 cycles per second frequency band. In general, the curves are seen to have the same characteristic shape.

Suppose now that a comparative analysis is made between the cold tests and the field tests. (See figs. 7 and 8.) Figure 7 shows that mufflers 1, 2, and 3 should have yielded their greatest attenuation at 280 cycles per second and no attenuation in one lower and one higher frequency cut-off band. A point-by-point comparison between the data of these two figures showed the helicopter noise spectrum was not reduced by the amount predicted for the muffler in the cold test. For instance, the cold-test data for muffler 2 showed about 11 decibels of attenuation was obtained at 128 cycles per second; the field test, however, showed that 7 decibels of attenuation was realized when the muffler was tested on the helicopter. Similarly, at 200 cycles per second, approximately 20 decibels of attenuation may have been expected but only 11 decibels were measured during the field test. These quantitative data inspections were made for all mufflers tested, and it was concluded that, although effective muffling was received, no muffler reduced the helicopter noise by the amounts predicted from the muffler cold tests.

Band-pass analysis.- In order to provide a rough check on the frequency-analyses data, certain band-pass analyses were made. These band-pass data (table I) give some pressure levels with overlapping octaves for frequency bands, ranging from 0 to 1200 cycles per second. Before further discussion of these data, it should be pointed out that the meter used in taking these measurements was of a different type from that used for the frequency analysis. A constant 2-decibel calibration difference was found to exist between the two meters used. For identical sound signals, the meter used to record the band-pass analysis always read 2 decibels more than the meter used to record the frequency spectrum.

Good agreement between these data was achieved in the frequency range of 75 to 400 cycles per second. This range is most important in the present study because most of the annoying noise falls within these limits. The band-pass analysis is not generally as useful for analyzing the data as the frequency spectrums; nevertheless, considerable advantage may be realized from such an analysis when it is used to check other data and to find regions of large sound energies.

Tail-pipe characteristics.- The theoretical data previously discussed (fig. 7) showed that certain pass bands occurred at frequencies both above and below those of the muffler resonance. For muffler 1, these bands are from 0 to 93 cycles per second and from 375 to 400 cycles per second. Although the theoretical data showed no attenuation should have been obtained in the frequency range from 0 to 93 cycles per second,

the frequency analysis of figure 8(a) indicates that some effective quieting was received. Some muffling was obtained where the high-frequency pass band should occur. In the high-frequency pass band, however, the attenuation is very small, ranging from 1/2 to 2 decibels. The marked decrease in attenuation in the frequency range from 375 to 400 cycles per second is sufficient to indicate that the tail-pipe resonance must have occurred in this frequency band; this result agrees with the predicted theory. The laboratory tests of this investigation also showed this attenuation decrease. It may therefore be concluded that the theoretical expression is valid for predicting the tail-pipe resonance of the muffler under engine-test conditions and that some slight attenuation may be realized during such resonances. Further evidence of these tail-pipe resonances may be found by checking the data for mufflers 2 and 3.

Internal sound pressures of the exhaust system.- As stated previously, the test engine had two separate exhaust manifolds, one exhausting three cylinders and the other, four. A schematic drawing showing this arrangement appears in figure 9. Sound-pressure data, as signaled by a crystal pick-up gage placed in the left exhaust manifold, are presented in figure 10. The curve of figure 10(a) describes one cycle of this sound variation. The curve of figure 10(b), having 4 humps, shows the exhaust-pressure variation for the 4-cylinder exhaust. This curve was not obtained directly from recorded data but was synthesized with the aid of the measured 3-cylinder exhaust curve.

Close examination of the plot showing the 3-cylinder exhaust pressure reveals that the sound pressure in the system did not go as high when the second consecutive exhaust valve opened as when the first valve opened. An examination of the exhaust system reveals that the first cylinder exhaust valve remains open for a considerable time after the second cylinder valve opens; thus, the volume of the system is increased. This increased volume allows, in effect, an immediate expansion of the exhausting gases and provides a damping of the peak sound pressures.

The maximum-peak exhaust pressure measured is shown to be approximately 7 pounds per square inch. This value corresponds to a sound-pressure level of 189 decibels. This pressure is far greater than both the pressure assumed in theory and the sound pressure used for the cold tests. The peak pressures measured entering the mufflers attached to the cold-test setup were of the order of 141 decibels or 0.028 pounds per square inch. In order to reduce large peak sound pulses, collector rings may be employed. The pressure records of figure 10, for example, indicate that, if a complete circular collector ring had been installed on the engine, the magnitude of the pressure peaks would have been reduced by over 50 percent. In addition, only one muffler would have been required.

Possible Reasons for Discrepancies Between Cold Tests and Field Tests

Some reasons may be given to account for the discrepancies that exist between the attenuations obtained from the cold tests and those obtained from the field tests. These reasons include (1) the large differences in operating conditions, and (2) the prevailing extraneous noises of the field tests.

Differences in operating conditions.- The differences that are known to exist in the operating conditions are those of large sound pressures, of internal flow velocities, and of high gas temperatures. The cold-test experiments were conducted with peak sound pressures of the order of 141 decibels (0.028 pounds per square inch); whereas the peak sound pressures from the engine entering the mufflers were about 189 decibels (7.0 pounds per square inch). This sound-pressure increase of 250 times in the muffler system raises the sound pressure to a point where it is no longer small with respect to the static (atmospheric) pressure. An original assumption made in the development of the theoretical equation was that the sound pressure would be small in comparison to the static pressure. Since it is obvious that this assumption $\left(\text{a small } \frac{p_{\text{sound pressure}}}{p_{\text{static pressure}}} \text{ ratio}\right)$ was not satisfied during the field tests, the attenuation decrease of the mufflers is most likely a function of the ratio $\frac{p_{\text{sound pressure}}}{p_{\text{static pressure}}}$. The quantitative manner in which this ratio affects the attenuation characteristics of the mufflers is not known; consequently, further muffler investigations are needed to determine the exact effects of this parameter.

Another very distinct difference between the cold tests and field tests was the internal flow velocity through the muffler system. For the cold tests there was no flow velocity as assumed in the basic theory; whereas for the field tests the exhaust flow velocity was estimated to be about 500 feet per second. The temperature measurements showed that this average velocity was approximately one-fourth the speed of sound in the exhaust system. This velocity may have had an appreciable effect on the quieting properties of the mufflers; yet no definite conclusions can be drawn until this velocity effect is further investigated. The 1200° F temperatures in the exhaust system were sufficiently high to have caused probably some temperature gradients, both within the muffler resonant chamber and between the internal tube and the resonant chamber. The magnitude of any such gradients and the influence on the muffler acoustics are not known. In conclusion, however, it may be stated that, although the individual effects of large sound pressures and exhaust-flow velocities are not known, their combined effects cause a reduction

in the attenuation of the mufflers over the greater part of the helicopter spectrum.

Extraneous noise.- Another factor which may account for some of the discrepancies between data is extraneous noise. The influence of this factor on the exhaust noise spectrum presented is difficult to determine. No pure extraneous noise spectrum could be obtained whereby a quantitative point-by-point comparison could be made. The extraneous noise, as discussed herein, is made up of all noises which originate from sources other than the exhaust gas. These noises include engine air intake, engine blower, engine clatter, vibrating fuselage, main rotor, and distant aircraft. The combination of these noises, when integrated with those from the exhaust gases, yields all the curves described in figure 8. If the exhaust-gas noise, however, is the most pronounced noise in a system and if it is reduced continuously toward zero, some point will be passed where the exhaust and extraneous noises will be equal. At this point the extraneous noise will be equally as important as the exhaust in determining the noise spectrum. Thus, the spectrum will stop defining the shape of exhaust noise in detail and begin to show some characteristics of the extraneous noises. A reduction of the exhaust noise well below that of the extraneous noise will leave a spectrum containing principally extraneous noise. Such a condition was strived for with the use of muffler 4. The curve for muffler 4 (fig. 8(b)) describing the spectrum of all exhaust gas in addition to the extraneous noise has practically the same shape as that of muffler 3. This observation indicates that muffler 3 must have reduced the exhaust noise to a point where the extraneous noise became prevalent and that muffler 4 could have only further reduced the exhaust noise; consequently, only slightly more over-all noise reduction was provided. Over-all sound-pressure measurements showed the same sound energy (81 decibels) was present at the microphones when both mufflers 3 and 4 were installed. Thus, the exact attenuation provided by the mufflers could not be determined because of the extraneous noise level. It is of interest to note here that, as the extraneous noise level is approached, the mufflers must reduce the exhaust noise in greater increments to reduce the over-all noise level by equal amounts. For instance, if the extraneous noise is 85 decibels and the exhaust noise is 100 decibels, the over-all noise will be 100.1 decibels. If a muffler reduces the engine noise by 12 decibels, the over-all noise will be reduced by 10.4 decibels to 89.7 decibels. If the engine noise is reduced another 12 decibels (to 76 decibels), the over-all noise level is reduced by only 4.2 decibels to 85.5 decibels. This explanation shows very clearly that the amount of noise reduction which can be gained by the use of a given muffler is dependent entirely upon the relative intensities of the extraneous and exhaust noises. It may be concluded, therefore, that a muffler used to attenuate a noise level which considerably exceeds that of the extraneous noise can provide much more over-all noise reduction than if it were working in a noise range close to the extraneous noise.

Significance of Measured Noise Reduction

In order that the significance of the noise reductions obtained may be interpreted, some comparisons and comments are made on the basis of the information contained in reference 6 regarding the sound levels of aircraft traffic. For those familiar with the noise of various types of airplanes on take-off, figure 27 of this reference provides a meaningful comparison. The noise of the unmuffled 180-horsepower helicopter has about the same intensity level as that of the 150-horsepower Stinson Voyager airplane or the 165-horsepower Beech Bonanza airplane. The smallest muffler tested on the helicopter reduced the intensity to about that of the quietest airplane of figure 27 of reference 6, a 65-horsepower Piper Cub airplane. These comparisons are made at take-off power at a distance of 200 feet. The three airplanes mentioned were all equipped with standard production mufflers.

As a further indication of the significance of the sound levels measured in this investigation, a comparison in terms of relative loudness is made. Relative loudness is defined herein, as in reference 6, as the perceived loudness of sound heard by the average ear relative to the loudness of the normal conversational voice at a three-foot distance. The variation in perceived loudness with the loudness level (in phons or decibels) is taken from the American Standards Association Standard Z24.2-1942. Relative loudnesses of the five configurations of this investigation, based on the over-all sound levels given in table I, are approximately 5.3 for the unmuffled helicopter, 2.9 with mufflers 1 and 2, and 2.5 with mufflers 3 and 4, all at a distance of 200 feet at take-off power. Thus, muffler 1, for example, reduces the loudness of the noise as perceived by the average ear by about 45 percent. This example gives an indication of the magnitude of the noise reduction obtained; although, of course, the human mind takes into account other factors besides loudness in judging the annoyance due to a particular noise. On the basis of the data in reference 6 the distances at which the helicopter noise would have the same loudness as the reference conversational voice are estimated at about 1800 feet for the unmuffled helicopter, 800 feet with mufflers 1 and 2, and 630 feet with mufflers 3 and 4. It is evident from this discussion that the mufflers produced a very significant reduction in the noise of the helicopter.

CONCLUSIONS

An experimental investigation has been made of the acoustical attenuation properties of four resonator-type mufflers by both laboratory and field tests. A survey of results of these tests show that the following conclusions may be drawn:

1. The resonator muffler can greatly aid in reducing the noise originating from the engine exhaust.

2. Most of the exhaust-sound energy for the engine tested is found concentrated at the lower frequencies from 70 cycles per second to 350 cycles per second. The mufflers were designed to produce maximum noise attenuation in this frequency band.

3. The attenuation of a resonator type of muffler, as determined from cold tests, can be expected to be in general agreement with theoretical calculations. Tail-pipe resonances occur in accordance with the theory and cause negative attenuation dips in the frequency spectrum.

4. Mufflers operating under field-test conditions cannot be expected to yield the attenuation as predicted by theory or cold tests but will yield less attenuation. Exact quantitative attenuation measurements could not be made because of the relatively high extraneous-noise level that existed during the muffler field tests.

5. The sound pressures inside the exhaust pipe are much larger than those assumed in the basic theory and constitute a probable cause for the differences existing between the field-test and the theoretical data. Further tests are necessary to isolate the effects of exhaust gas flow velocities and large sound pressures on the attenuating properties of the mufflers.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 20, 1953.

1 atmosphere = 10^6 dynes
1 psf = 480 dynes

400 dynes = 126 db
800 dynes = 132 db

$db = 20 \log_{10} P + 74$

1 dyne = 1 gram-cm/sec^2

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TABLE I

BAND-PASS ANALYSIS OF HELICOPTER NOISE AT 200 FEET

Muffler	Over-all sound level, db	Sound-level pressure, db, from -								
		0 to 50 cps	50 to 100 cps	75 to 150 cps	100 to 200 cps	150 to 300 cps	200 to 400 cps	300 to 600 cps	400 to 800 cps	600 to 1200 cps
1	85	72	80	81	81	77	75	70	60	54
2	85	70	79	82	81	76	73	69	60	58
3	83	70	78	80	79	74	72	67	60	57
4	83	70	78	80	78	73	72	67	59	58
No muffler	91	74	84	88	87	83	81	71	61	58

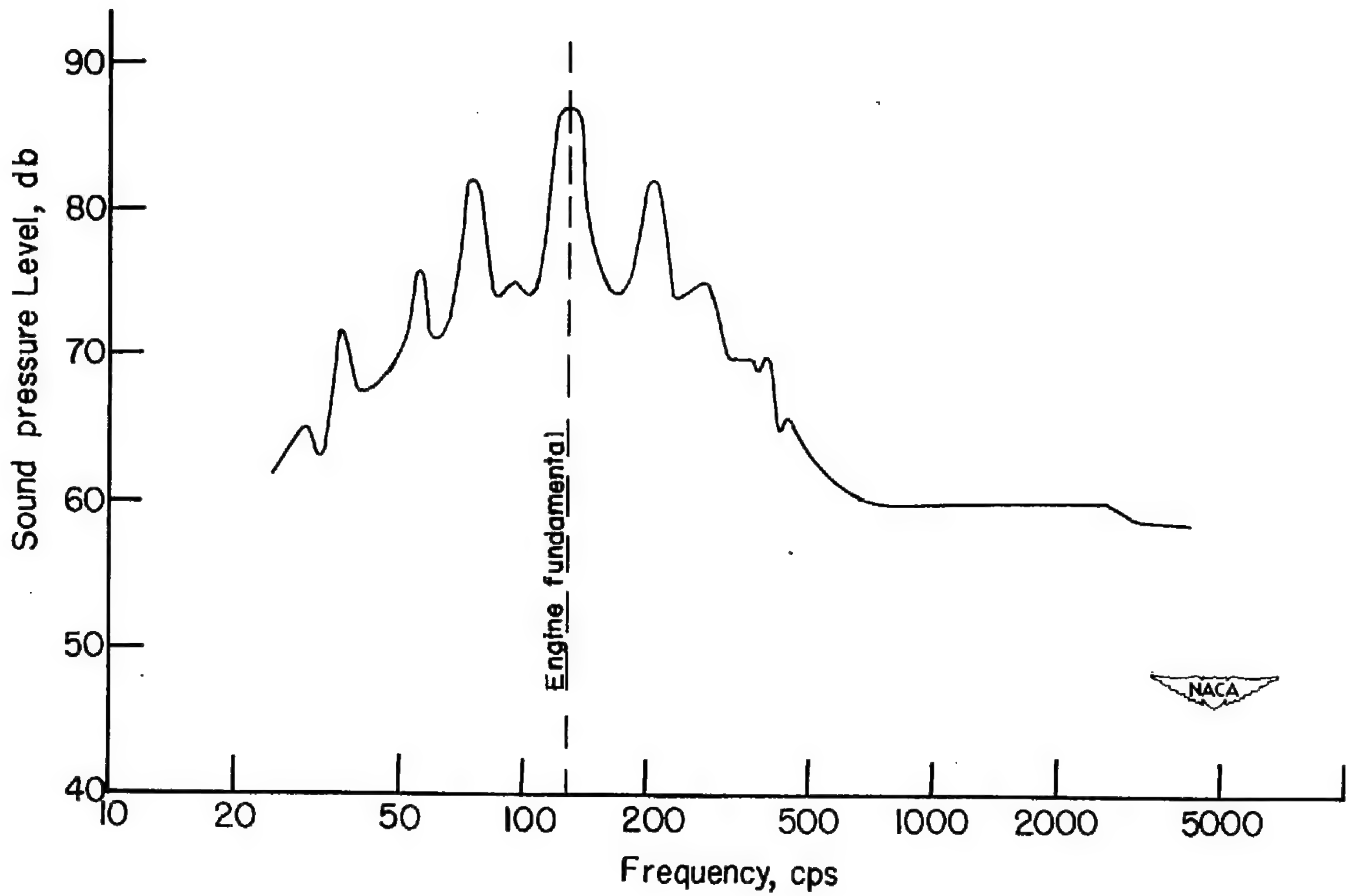


Figure 1.- Unmuffled-helicopter-noise frequency analysis.

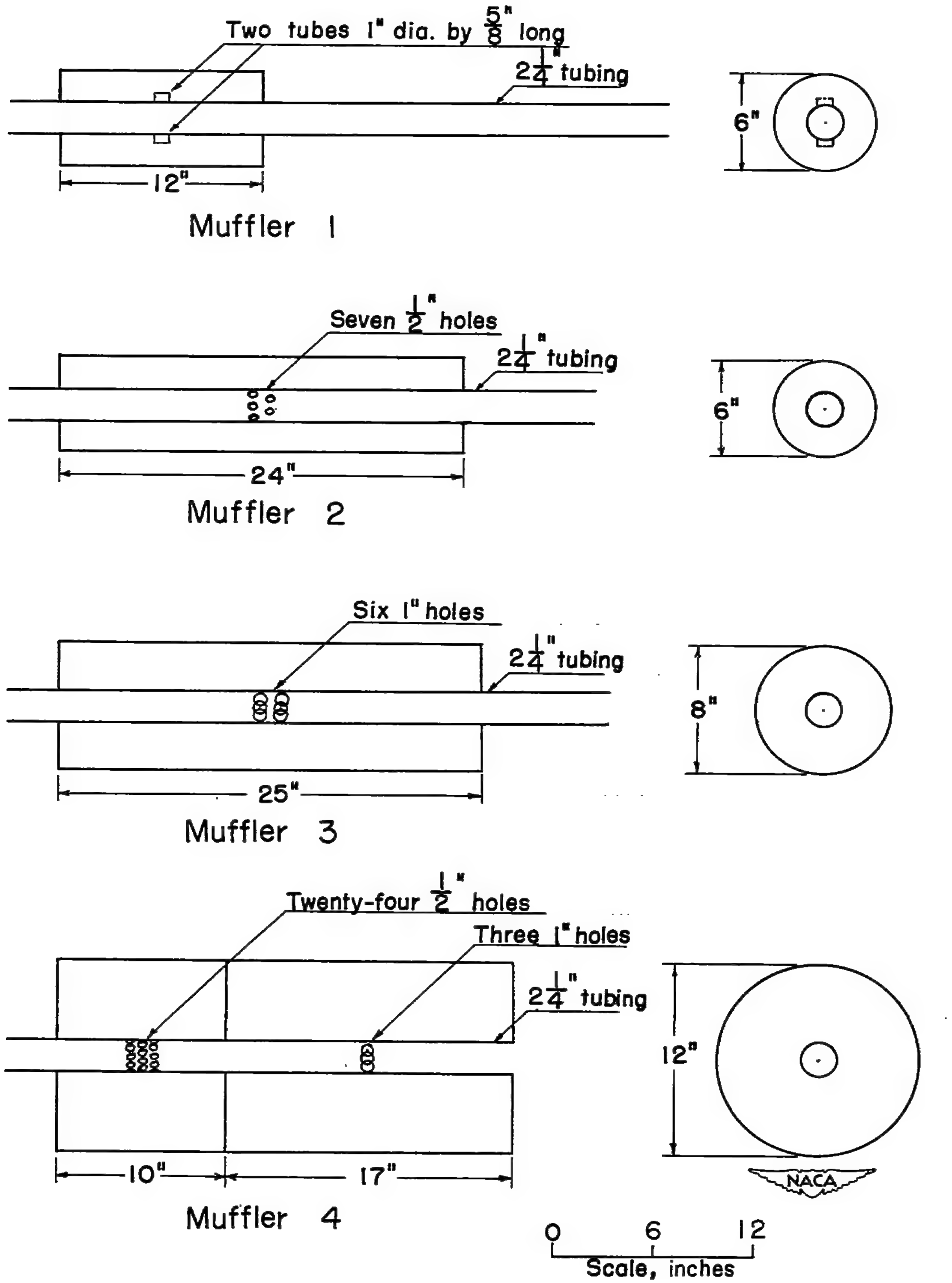


Figure 2.- Sketches of mufflers tested.

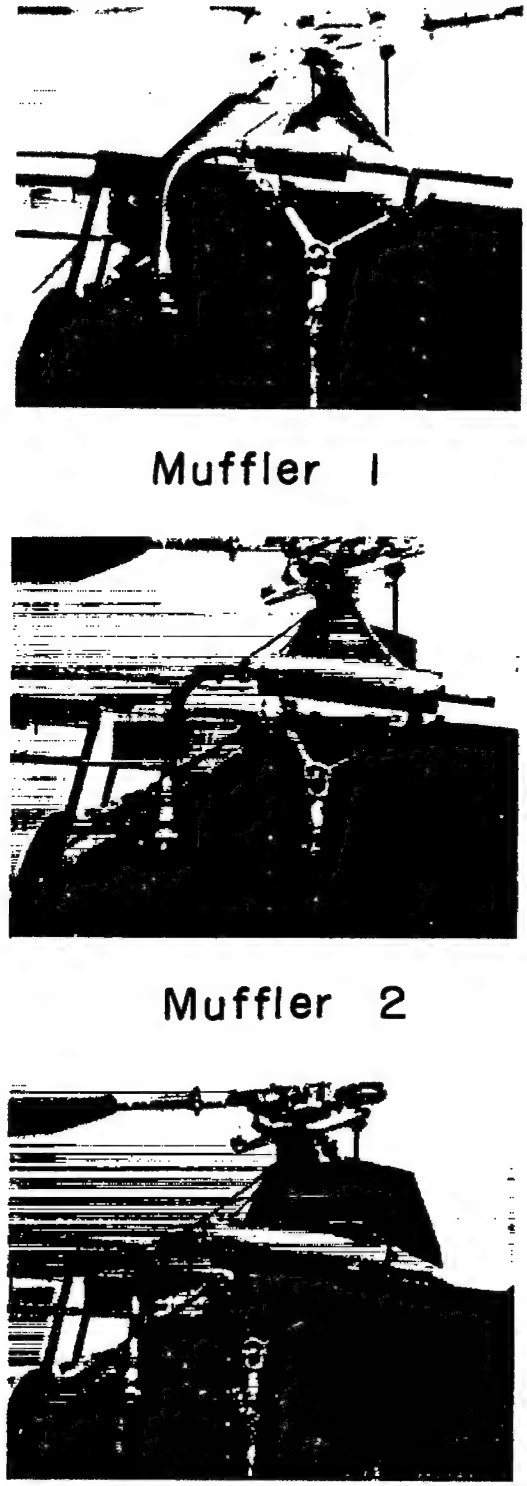


Figure 3.- Muffler installation.

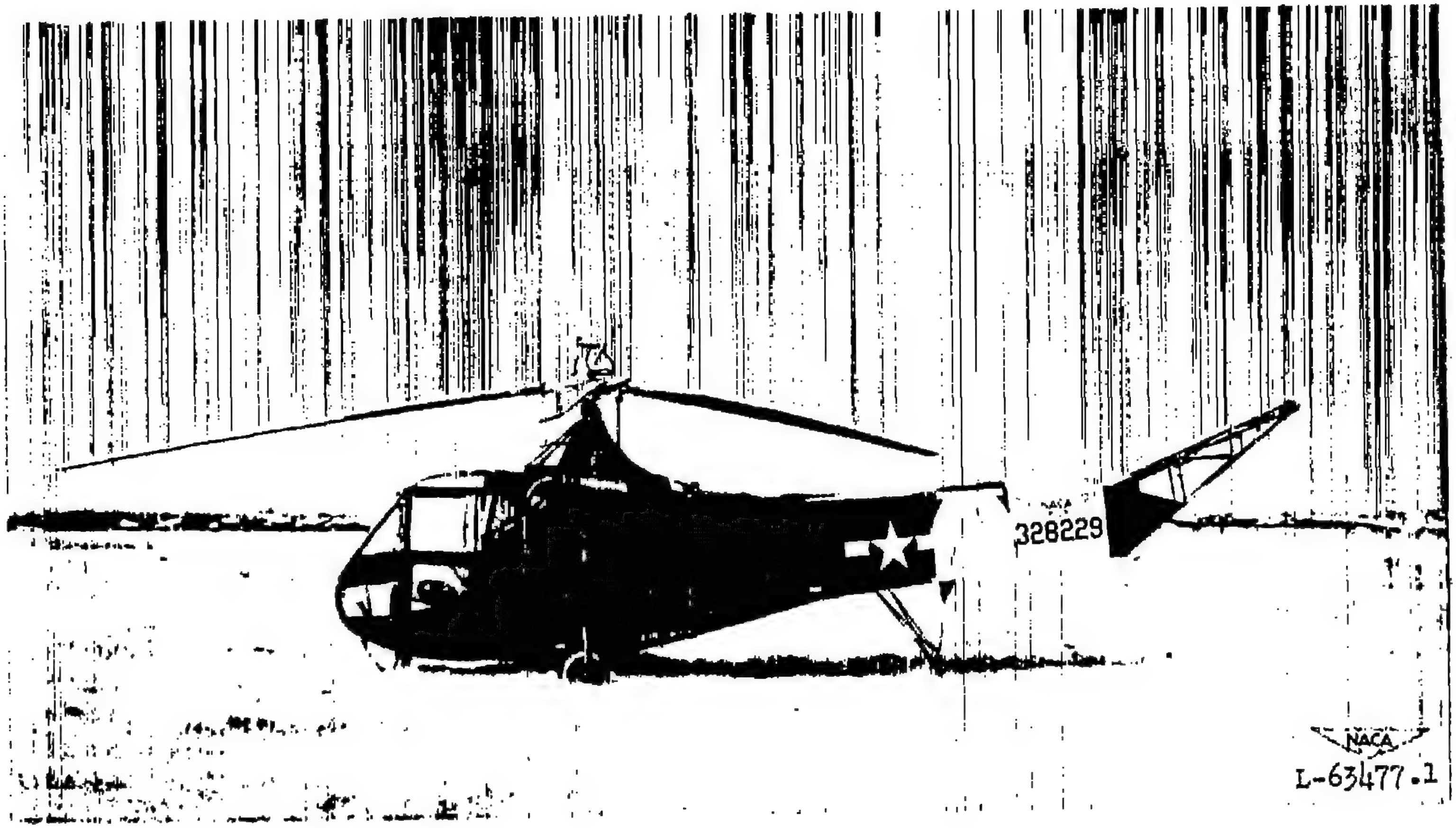


Figure 4.- Muffler 2 installed on helicopter with tail rotor removed.

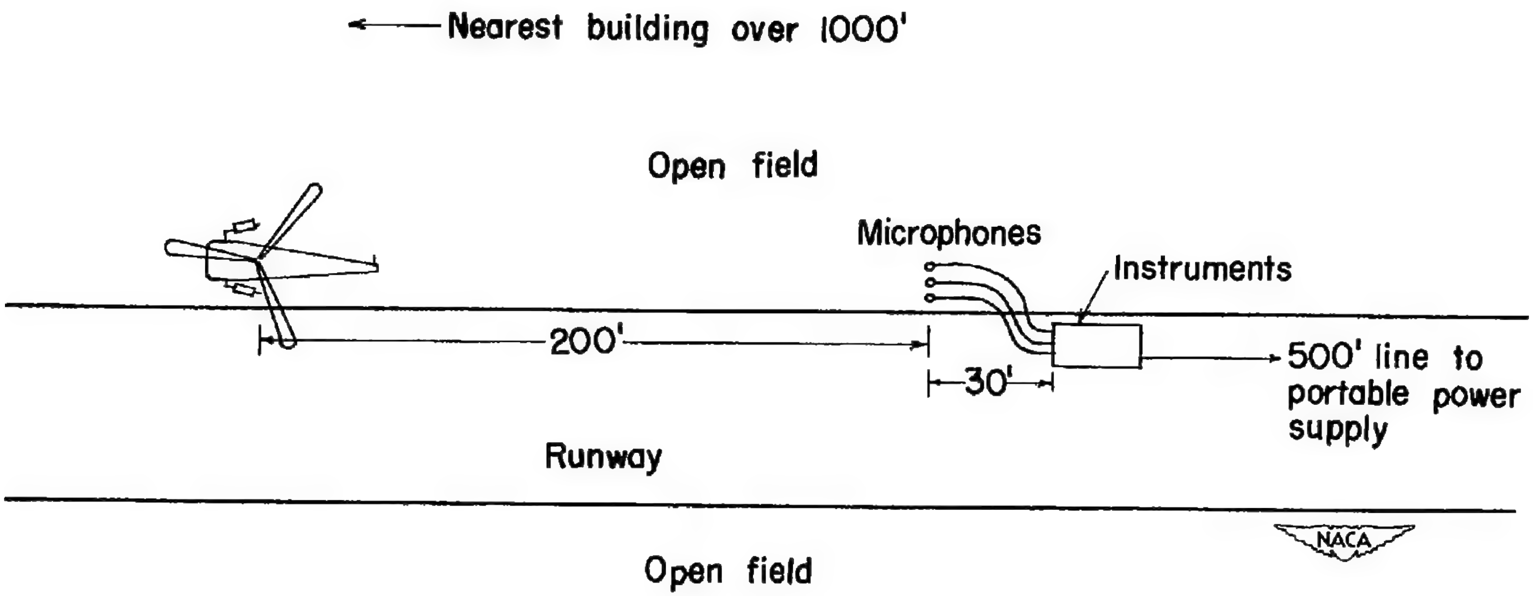


Figure 5.- Field-test arrangement.

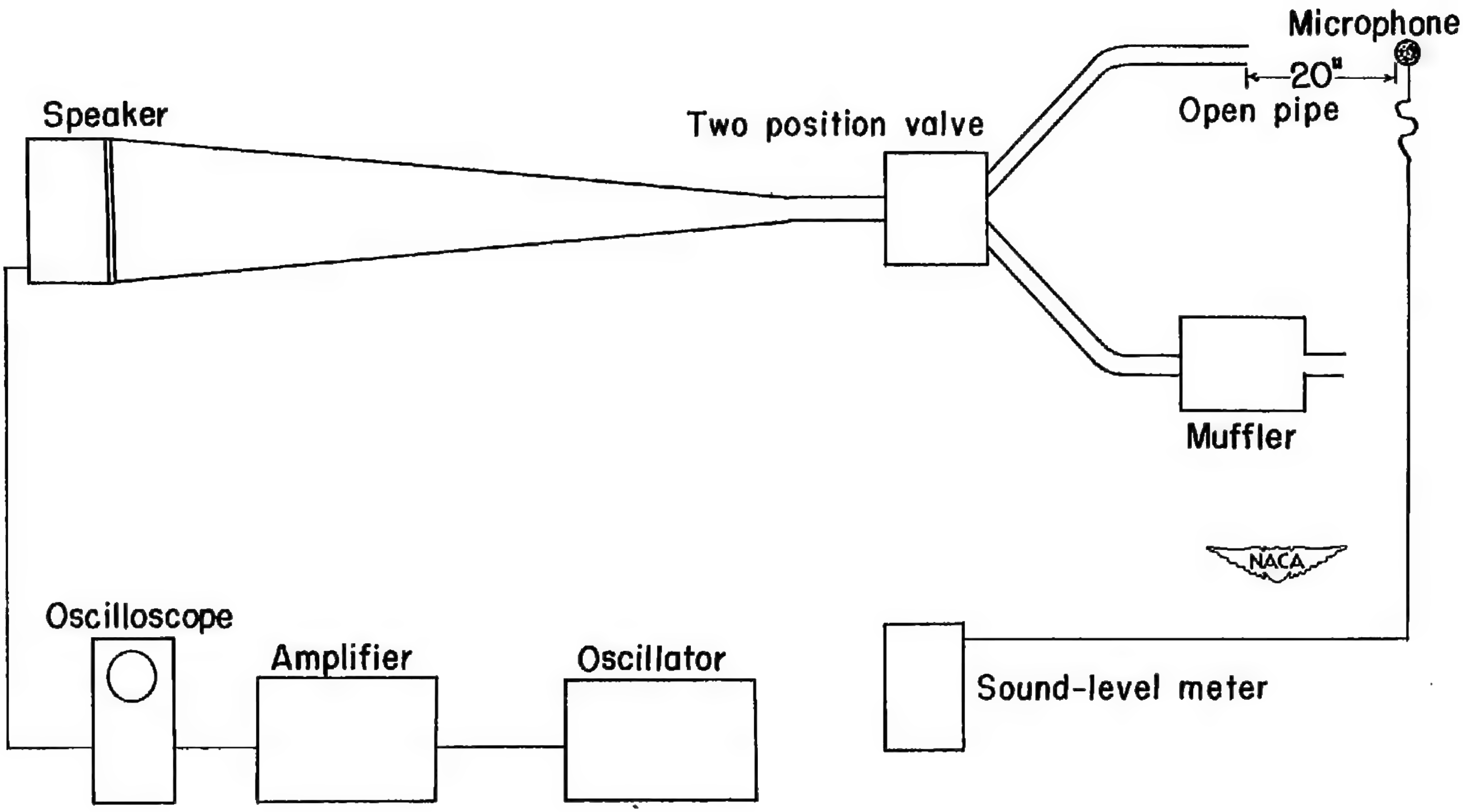


Figure 6.- Schematic diagram of the arrangement of apparatus for cold test of mufflers.

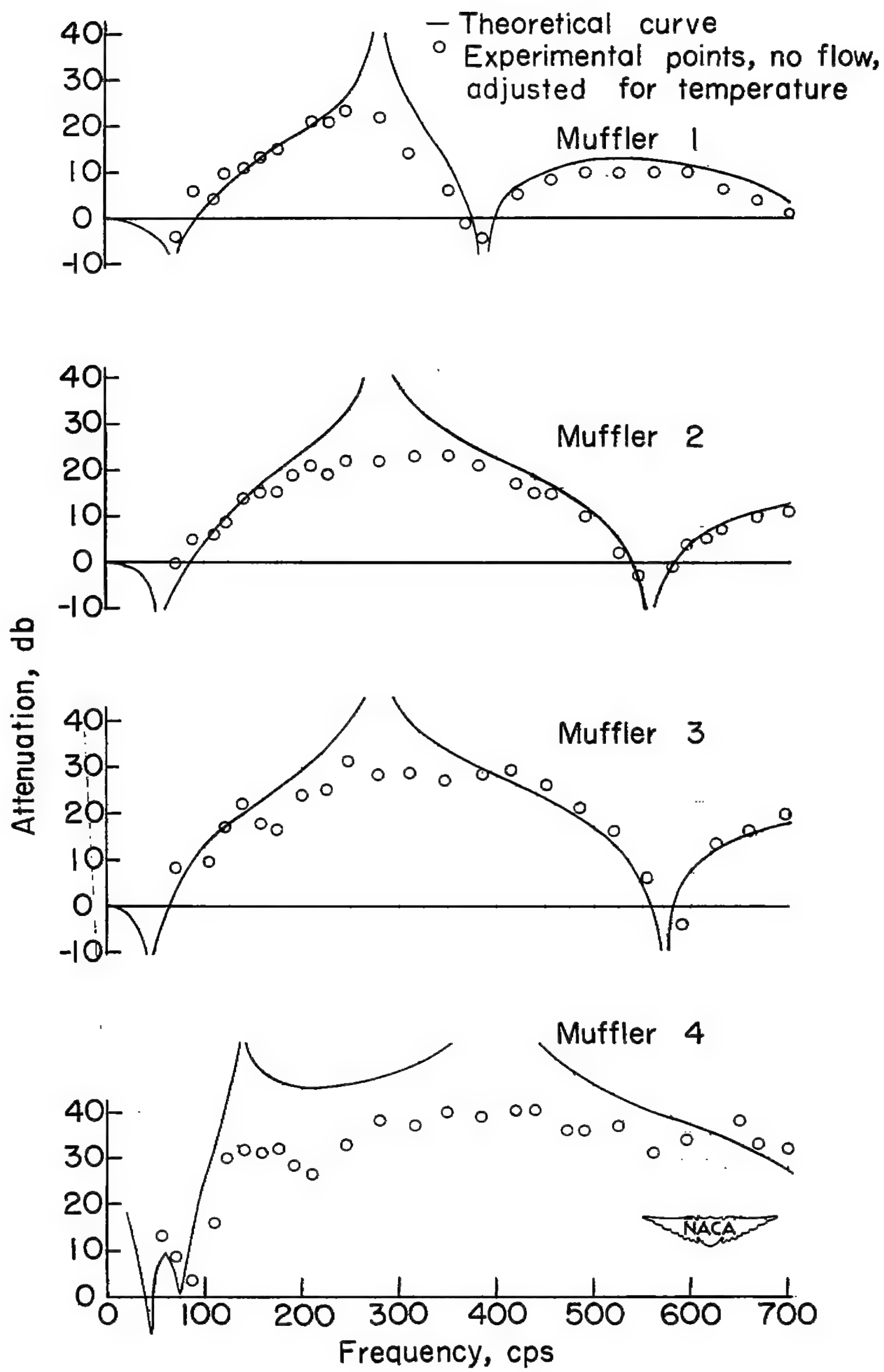
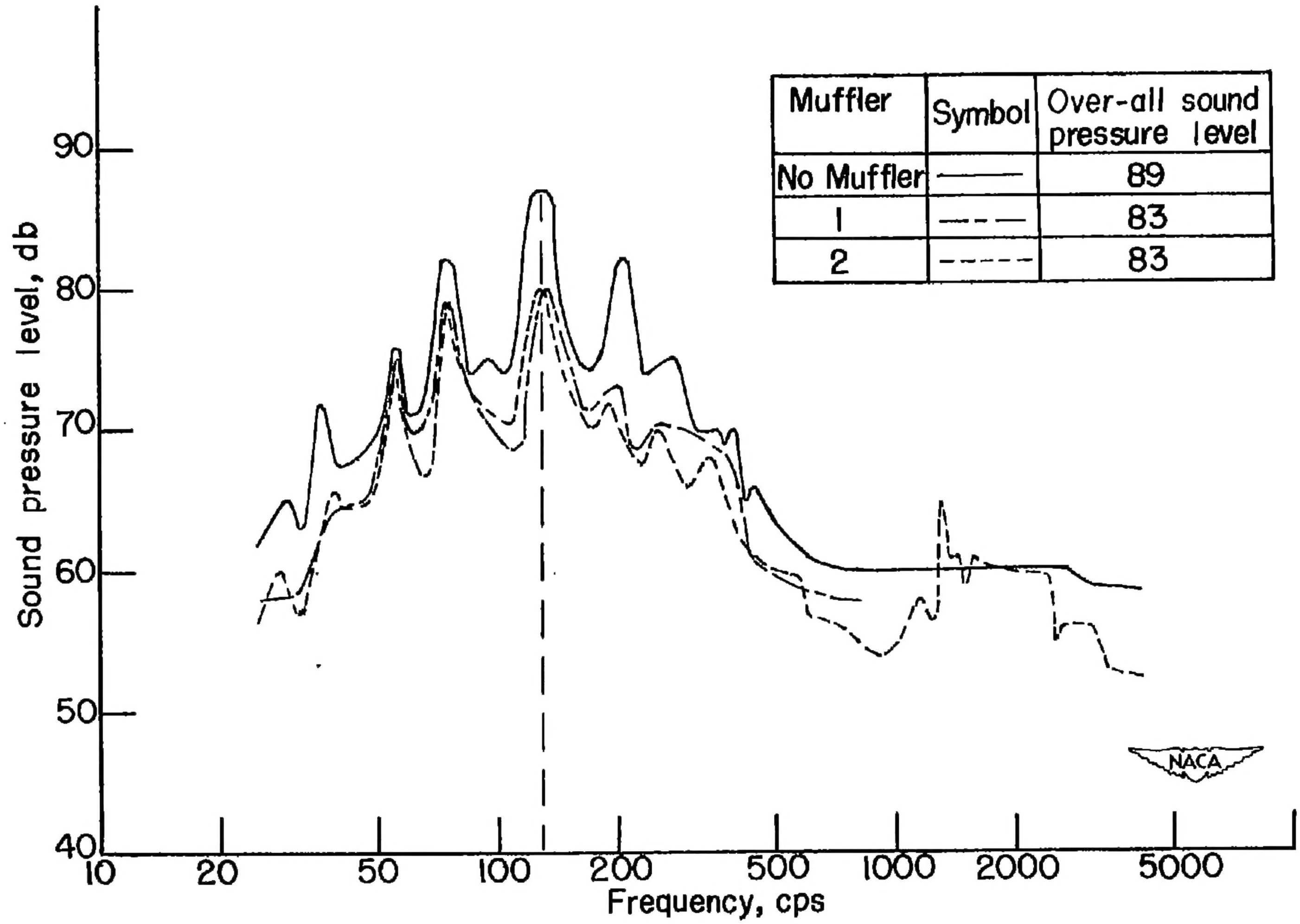
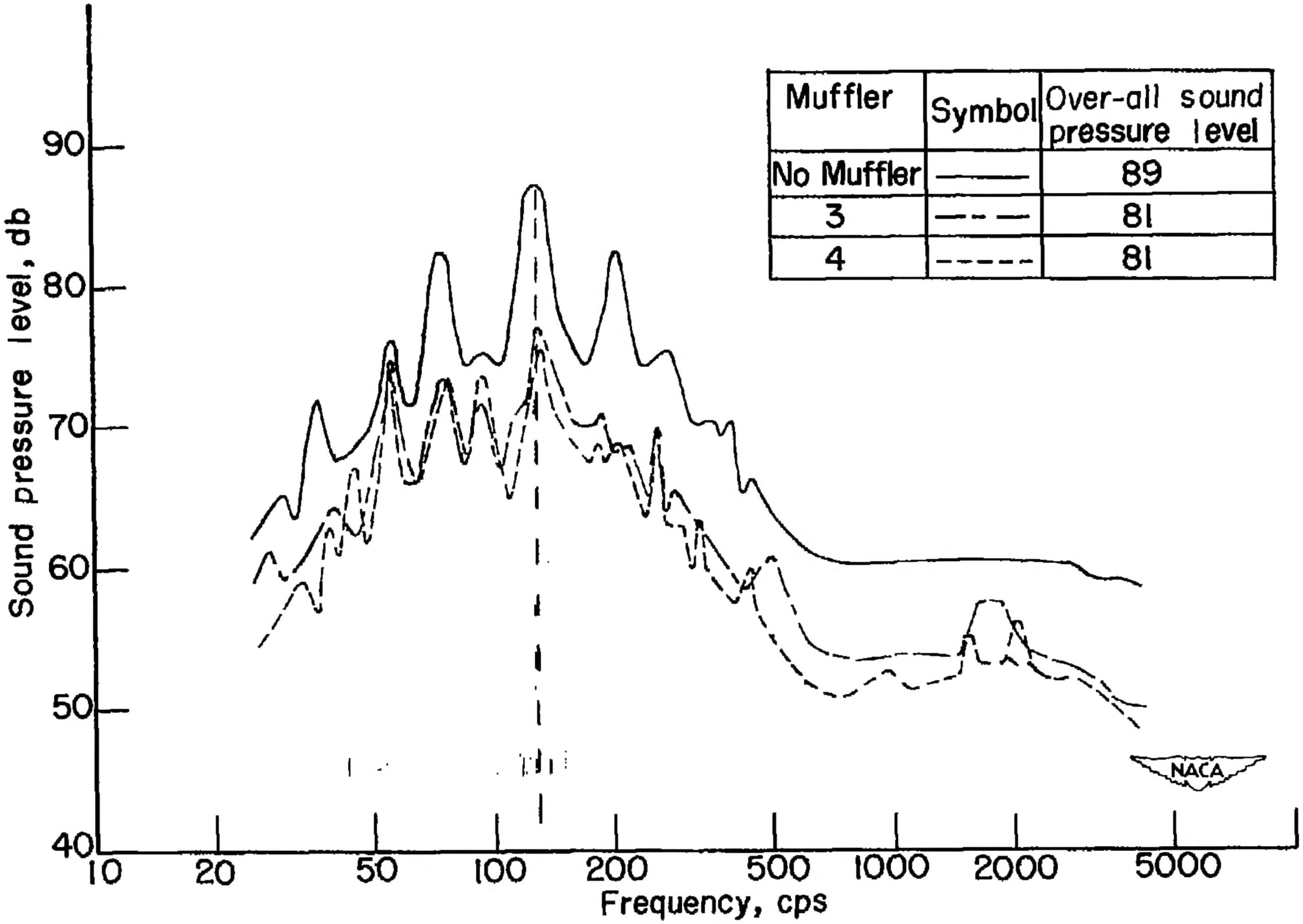


Figure 7.- Cold-test data and theoretical curves for mufflers tested.



(a) Mufflers 1 and 2.

Figure 8.- Comparison of recorded frequency analyses of helicopter noise with and without mufflers.



(b) Mufflers 3 and 4.

Figure 8.- Concluded.

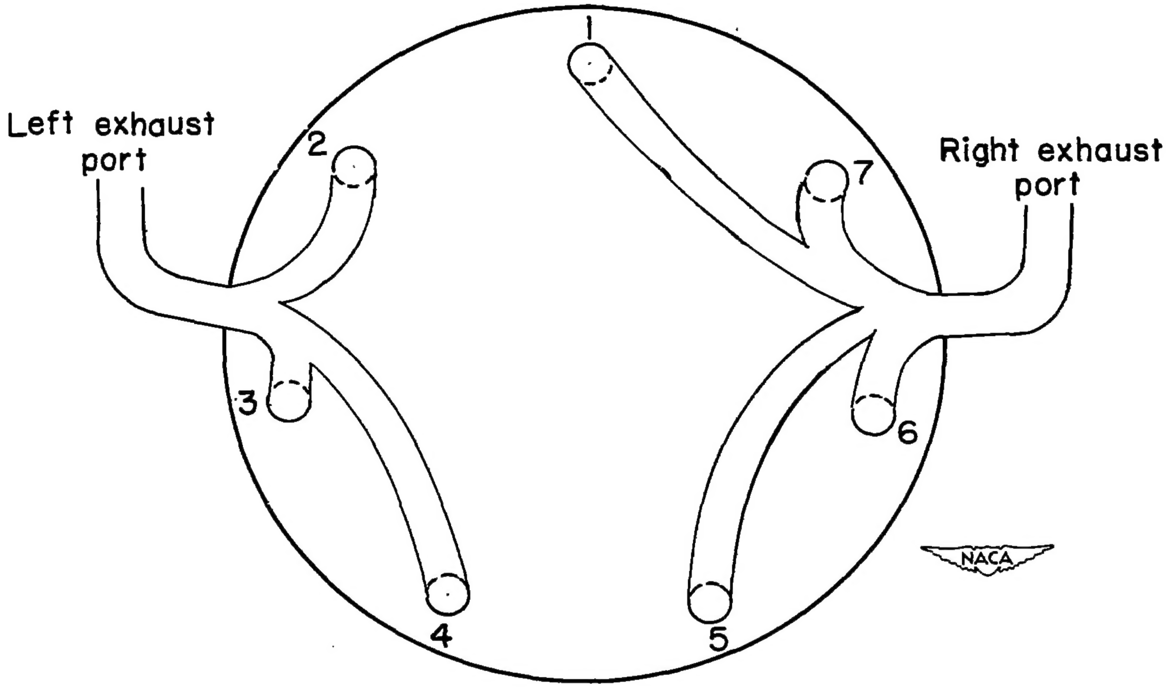
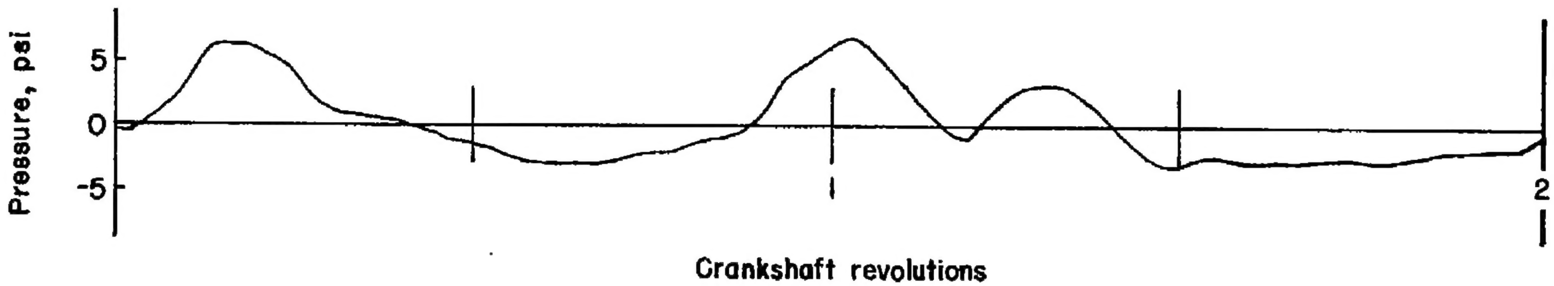
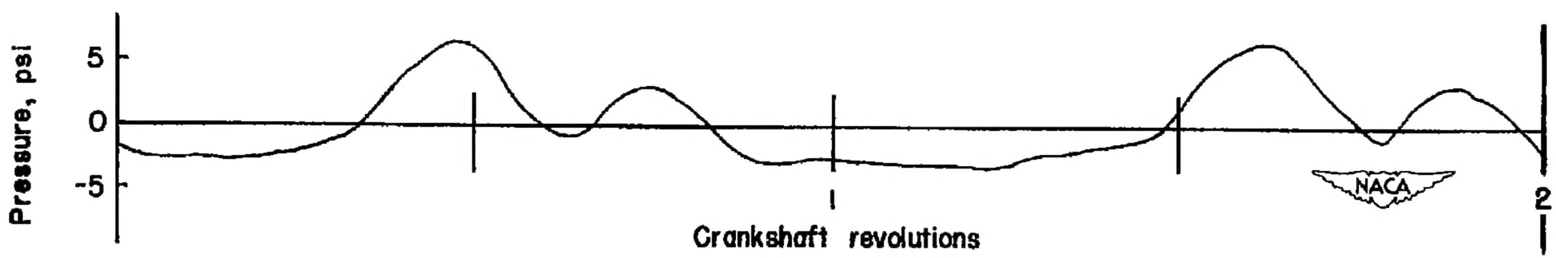


Figure 9.- Schematic drawing of helicopter-engine-exhaust system.
Firing order: 1, 3, 5, 7, 2, 4, 6.



(a) Variation of sound pressure measured in the three-cylinder exhaust of the test helicopter.



(b) Variation of sound pressure in the four-cylinder exhaust of the test helicopter as estimated from three-cylinder data.

Figure 10.- Exhaust-pipe sound pressure.

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